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Lubrication

A Technical Publication Devoted to the Selection and Use of Lubricants

This Issue

FUNDAMENTALS OF WEAR

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LUBRICATION

A TECHNICAL PUBLICATION DEVOTED TO THE SELECTION AND USE OF LUBRICANTS

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FUNDAMENTALS OF WEAR*

OF THE many diverse functions a lubricant may perform, such as cooling, sealing, etc., the most common is the reduction of wear and friction. The importance of wear and friction in controlling the useful life of machinery and the efficiency of operation is appreciated by all concerned with design, operation and maintenance. Equally apparent is the great complexity of these two phenomena and the need for their intelligent control.

The treatment of many lubrication problems has been, and is today, essentially empirical. Thus, the compounding of lubricants has depended mainly on trial and error approaches, such as investigating systematic variations on a proven lubricant type. Lubricant testing methods generally depend on the simulation principle, in which actual conditions of field operation are duplicated as closely as practicable in the laboratory.

While this general approach has a record of effectiveness, it has become progressively less efficient with the increasing variety and complexity of modern lubrication problems. It is clear that the testing facilities required for this general method of operation will become inordinately extensive and costly.

A rather wide gap exists between the fundamental and the applied phenomena of friction and wear, although much has been done during recent years to narrow this area and bring the two closer together. This article reviews the basic knowledge which has been developed in this field and discusses how it may be applied to the understanding of problems in lubrication, particularly of metal surfaces and liquid lubricants.

This realization has led to an increasing emphasis on the fundamental approach, which attempts to understand all lubrication problems in terms of the interplay of a relatively few simple basic physical and chemical processes; solutions to specific problems are then deduced from this general understanding.

The great advantage of the fundamental approach is that knowledge gained in the solution of one problem is directly applicable to the solution of any others, since it clarifies general concepts. A disadvantage lies in the difficulty of applying theory to real practice while basic principles are still not clearly understood.

Although much significant work has been done on the fundamentals of friction and wear in the past few decades, a rather wide gulf persists between the fundamental and the applied. It is the purpose of the present review to survey the state of basic knowledge in this field and to indicate how it may be applied to the understanding of problems in lubrication, particularly of metal surfaces and liquid lubricants.

*As is customary, the December issue is prepared by the Research Division.

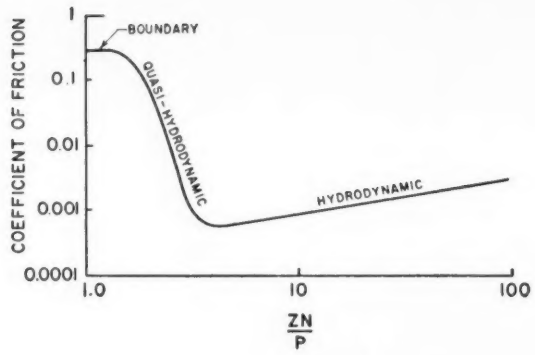

Figure 1 — Definition of Lubrication Regimes.

It is proposed to consider: (1) the various phenomena associated with the sliding of bearing surfaces; (2) the basic processes involved in the particular phenomenon of wear (and friction) and the contributing effects of surface films; and (3) interpretation of some typical lubricant performance characteristics in terms of these basic processes.

PHENOMENA ASSOCIATED WITH SLIDING

In engineering practice, it is usual to attempt to operate mechanisms with a fluid film separating bearing surfaces. This occurs in the hydrodynamic region of Figure 1. This figure is the familiar plot of coefficient of friction against the product of lubricant viscosity, Z; speed, N; and reciprocal load, 1/P. In the region of high ZN/P, the pressure developed in the fluid film between the bearing surfaces supports the load between the surfaces.

At the low ZN/P extreme of Figure 1 is the region of boundary lubrication in which there is no direct dependence of coefficient of friction on bulk lubricant viscosity. In this region, contact between the bearing surfaces supports the load, and the coefficient of friction depends on the chemical and physical properties of the surfaces. Between these boundary and hydrodynamic lubrication regions is a mixed-region in which the bearing load is partly supported by pressure developed in a fluid film and partly by surface-to-surface contact. This is generally referred to as the quasi-hydrodynamic region of lubrication.

Almost all mechanisms operate part of their life in the boundary and/or quasi-hydrodynamic regions of lubrication. Some simply pass through these regions while starting or when subjected to vibration. Others such as piston rings and worm gears regularly operate in these regions. As a result of the surface-to-surface contact, wear occurs. The principal mechanisms of this wear are undoubtedly the same in both quasi-hydrodynamic and boundary lubrication. Because the latter regime is simpler and more amenable to treatment, the discussions below will be confined to it.

"Laws" of Friction and Wear

Since the load in boundary lubrication is supported by surface-to-surface contact, the nature of these surfaces must be considered. The smoothest bearing surfaces that are common in engineering practice have roughness of the order of a few microinches. Thus, even these surfaces have hills or asperities which are hundreds of metal atoms or tens of typical lubricant molecule lengths in height.

When one surface slides over another, a friction force opposes the sliding. The friction force is roughly proportional to the load normal to the surfaces and independent of the apparent area of contact between the surfaces. This is the well known Amonton-Coulomb Law.

This law can be simply derived by considering what may happen when two bearing surfaces are brought into contact under load. Bowden and coworkers[12] have shown that when two surfaces are pressed together with a load, W, only the opposing high spots make contact as shown in Figure 2. The pressures at these local areas of true contact exceed the plastic flow pressure, p, of the softer of the two surfaces; the asperities flow until the true area of contact, A, is sufficient to support the load without further plastic flow. Thus,

$$A = \frac{W}{p} \qquad (1)$$

At the area of true contact, the surfaces are in such intimate contact that they cold weld or adhere; this cold welding due to normal loading has been confirmed by radioactive tracer studies[37]. In order for the surfaces to slide, it is then necessary to break these adhesions which have a shear strength, s. Hence, the friction force, F, which resists sliding is

$$F = sA \qquad (2)$$

Combining (1) and (2) yields the following expression for f, the coefficient of friction

$$f = \frac{F}{W} = \frac{s}{p} \qquad (3)$$

The coefficient of friction is thus independent of the load and of the apparent area of contact, as required by the Amonton-Coulomb law. Since both

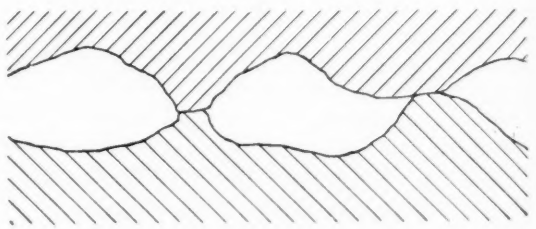

Figure 2 — Unlubricated Bearing Surface.

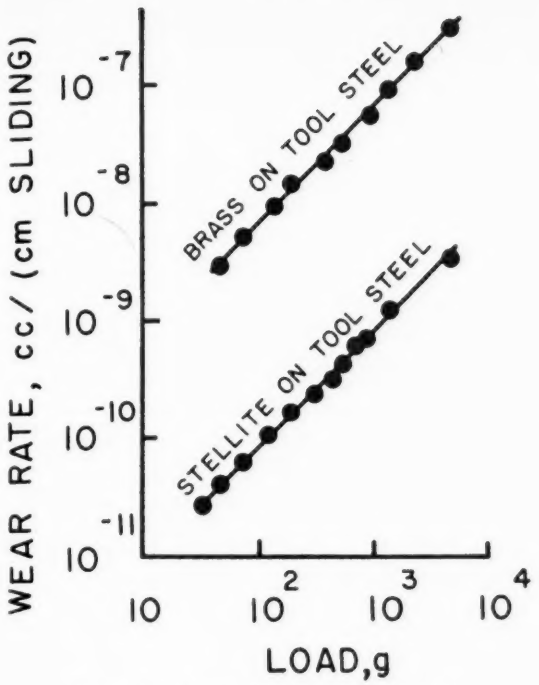

Figure 3 — Normal Wear-Load Relationship.

s and p are measures of the strength properties of the softer metal and approximately equal, the coefficient of friction should be near unity; this agrees roughly with observed values for sliding of nominally clean dry surfaces.

In addition to friction, attrition of the sliding surfaces is observed. This wear, V, on a volume or weight basis, also increases roughly proportionally to the load and is independent of the apparent area of contact. It also increases linearly with the distance of sliding, L.[2, 17] This may be expressed as

$$V = k\,WL \qquad (4)$$

in which k is the constant of proportionality called the "specific wear rate". Figures 3 and 4 show some of the experimental evidence for this relationship which also has been derived theoretically.[1]

There are indications[17] that k may be inversely proportional to the indentation hardness of a given material. However, this inverse relationship does not appear generally valid for unlike bearing materials.[2]

These "laws" of friction and wear, as expressed in the above equations appear to hold over a substantial range of conditions. However, particularly in the case of wear, deviations often occur. Such deviations are most commonly observed when (1) the usual air atmosphere is absent, (2) highly effective boundary lubricants are present and (3) high loads, speeds and temperatures are employed.

Associated with the sliding of bearing surfaces are a number of phenomena which tend to modify our understanding of wear and friction as expressed by the above "laws". These phenomena are briefly considered below.

Frictional Heating

Both friction and wear are influenced by temperature, since it affects both the physical and chemical properties of surfaces and lubricants. In turn, temperature of bearing surfaces is greatly influenced by friction since most of the frictional energy appears as heat.[8]

The rate of frictional heat generation will be proportional to the product of the friction force and the sliding velocity. This heat generation is concentrated in the small volume of the contacting asperities which leads to very high temperature flashes. In general, the magnitude of the temperature flashes will depend on the rate at which heat can be conducted away from asperities as well as on the load and sliding speed.[8, 12] Figure 5 illustrates combinations of load and speed required to generate a given temperature (that which produces a photographic record of the hot spots) on a glass surface against riders of varying thermal conductivity.[12] It has been shown that the maximum temparature that may be obtained in such flashes at asperities is generally the melting point of the lower-melting bearing material.[12, 13]

Friction Induced Vibration

Sliding speed has an effect on friction and wear in addition to its effect on bearing surface temperatures. This is a kinetic effect since sliding speed controls the time available for formation of strong welds between the bearing surfaces and also the time available for the surfaces to interact with the lubricant. In general, it is found that the static coefficient of friction is greater than the kinetic coefficient of friction except in the presence of an effective boundary lubricant.[12] This decrease in friction with increasing speed in combination with the elastic and inertial properties of the bearing

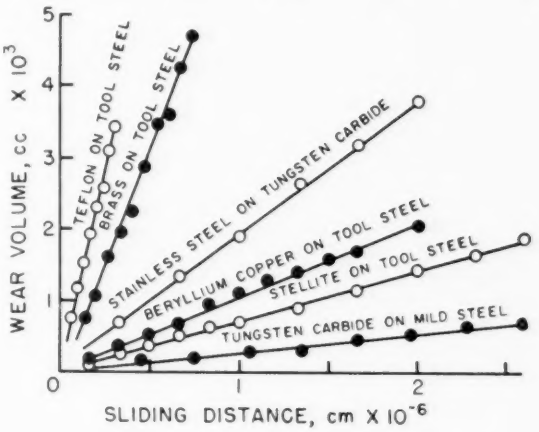

Figure 4 — Wear and Sliding Distance.

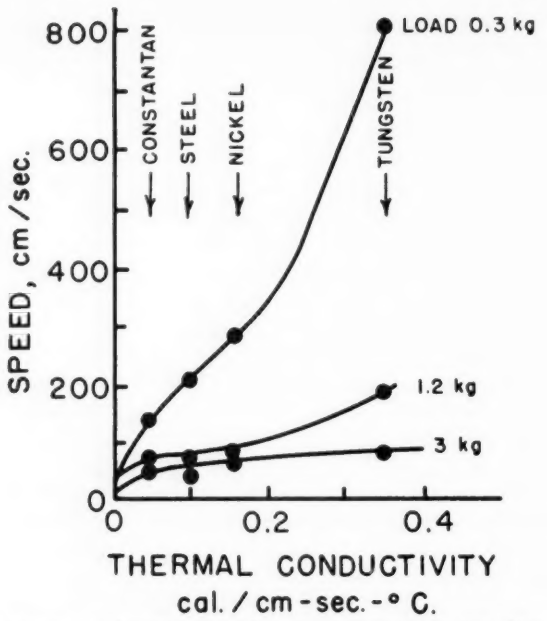

Figure 5 — Conditions to Produce Photographic Hot Spot Record.

may produce "stick-slip" action, or the more familiar squealing or chattering of the bearing.[11,12]

Gross Surface Failures

Under some conditions of sliding, the bearing surfaces will scuff, seize, flow or wear at an unusually rapid rate. The exact mechanisms of these phenomena are not well understood. However, it appears that in general this condition is associated with very high unit loading coupled with high surface temperatures and high friction. Such a situation can foster either growth of the welded junctions or gross plastic flow of the surface; in either case, large areas of the surface become involved.

The effect of load is shown in Figure 6 for very low sliding speed and room temperature.[17] This figure indicates that at apparent bearing pressures greater than approximately a third of the Brinell or Vickers hardness,* specific wear rate increased very rapidly with increasing load. Burwell and Strang attributed this increase to trapping of wear particles between asperities at higher loads with consequent "snowballing" of wear.

Studies[35,36] of the effect of sliding speed and temperature on friction and wear show that when the coefficient of friction exceeds about 0.2, mass surface failure of test specimens is obtained under high load conditions. Hence, it appears that high friction may contribute to catastrophic bearing surface failure, presumably by increasing surface temperature[32] and by fostering junction growth and surface plasticity. It follows that these surface failures will be self accelerating.

*Brinell or Vickers hardness values are expressed as pressures.

Run-in

Gross bearing surface failure is perhaps most often observed during the run-in of new or newly overhauled mechanisms. The reason appears to stem from the fact that new machine parts cannot generally be manufactured with sufficient precision to avoid some misalignment. This places high loads on apparent areas of contact that may be much smaller than the design areas.

When sliding commences, rapid wear will generally occur as a result of high pressure. However, with a properly designed mechanism and a proper lubricant, this rapid wear will expand the apparent contact area sufficiently to prevent the self-acceleration characteristic of gross surface failure.[16]

Usually the high wear and friction during the transient run-in period are followed by lower "steady-state" values. This appears to be associated with changes in the physical[29,30] and chemical[7] nature of the surfaces, as well as with the increased contact area.

BASIC WEAR PROCESSES

In the previous paragraphs, various phenomena that are associated with friction and wear have been briefly discussed. In attempting to analyze the broad picture of wear it is convenient to consider the basic processes involved. These appear to be:

(1) adhesion or welding at local areas of two bearing surfaces. This results in transfer of material between the surfaces and plastic distortion of the surfaces.

(2) cutting or plowing when one surface is appreciably harder than the other or one surface is more ductile than the other. In this case, the asperities on a hard surface remove material by plowing through softer or more friable surfaces. This is essentially a microscopic version of the usual metal cutting process in which a hard tool

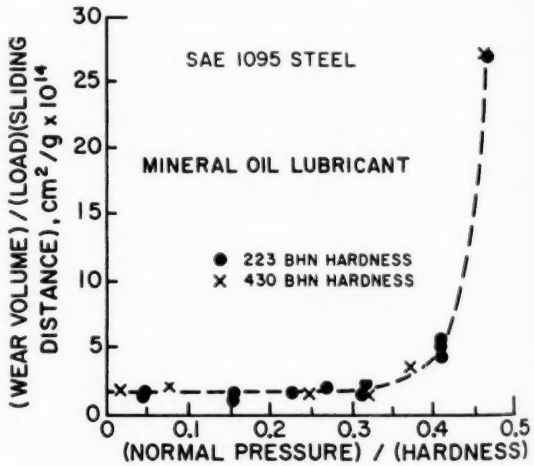

Figure 6 — Wear Dependence on Load and Hardness.

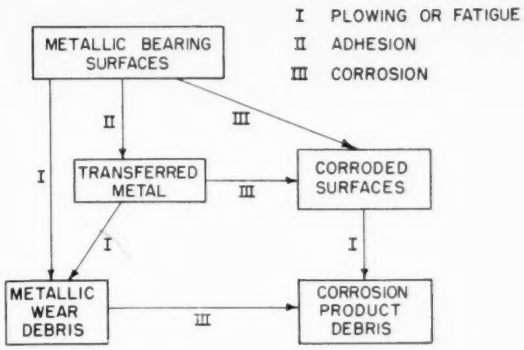

Figure 7 — Wear Mechanisms.

plows through the softer workpiece. If the harder surface is a third body such as dust or wear particles, this is generally known as "abrasive" wear.

(3) corrosion which consists of chemical reaction of the metal surface with its environment. This chemical reaction may range from simple oxidation by air to that produced by extreme pressure lubricants (e.g. active sulfur-chlorine gear lubricants).

(4) fatigue in which particles of surface material suddenly separate from the surface as a result of repeated stressing. On a macroscopic scale, this is generally called pitting or spalling.

In almost all practical systems, wear occurs by combinations of the above basic processes. The combinations that appear to be of principal importance are outlined as paths in Figure 7. In the following discussions, an attempt will be made to summarize present knowledge concerning these paths by which wear takes place.

Direct Generation of Wear Debris (Paths I and I-III)

In the sliding of one surface over another the surfaces are repeatedly stressed. Eventually sufficient strain energy may be accumulated in the metal lattice to cause fracture with subsequent separation of loose metallic wear particles. This surface fatigue mechanism with the production of large wear particles (10^{-1} to 10^{-2} inches) is frequently observed in rolling contact bearings, gears, valve lifters and cams. This macroscopic surface fatigue process has been shown to depend in part on the chemical composition of lubricants; however, the mechanism of this dependence is not clear.[4,19]

A microscopic version of this fatigue process has been suggested[18] as a normal wear mechanism. In this case the wear particle size presumably would be much smaller (10^{-3} to 10^{-4} inches). There is a limited amount of indirect evidence supporting this thesis.[22]

When one surface is considerably harder than the other, asperities on one surface may plow through the opposing asperities. This may create loose wear particles and an additional friction force over and above the adhesion force. The plowing contribution to friction apparently will be generally small.[12] It does, however, account for the increase in friction and wear with surface roughness observed in some systems.[15,21] Plowing may be an important factor during run-in when initial surfaces are rough.

Generation of Wear Debris Through Metal Transfer (Paths II-I and II-III-I)

In addition to direct generation, there is considerable evidence that loose metallic wear debris can also be generated by first going through a metal transfer step. This transfer occurs by the adhesion mechanism responsible for most of the friction force.

In the process of breaking the welded junctions between asperities, the strength and ductility of the junctions largely determine the friction and amount of surface damage that result.[33,41] If the surface materials adhere only very weakly, they tend to shear along the plane of the original contact with consequent low friction and little metal transfer. Silver on steel is an example of this type of junction. Other metals form brittle compounds which tend to break near the plane of original contact. Tin and iron are an example of this type of junction. On the other hand, readily soluble metal couples adhere strongly and, as a result of work hardening of the interface, tend to shear at a

Figure 8 — Metal Transfer Due to Sliding Between Single Crystals of Copper.

TABLE I

Effect of Atmosphere on Friction and Wear

	Atmosphere			
	Argon		Air	
Lubricant	f	V	f	V
Dry	0.46	67	0.36	6.2
Cetane	0.26	24	0.11	1.0
Wear Debris (Dry sliding)	All Metallic		75% αFe_2O_3 25% Fe_3O_4	

f = coefficient of friction

V = relative "steady-state" wear rate (weight basis)

plane different from the original interface; thus, an appreciable amount of metal transfer between surfaces takes place and the friction and surface damage are high. Two bearing surfaces of the same metal are an example of this type of couple, while nickel on steel is another. Figure 8 shows a transferred fragment and surface damage resulting from sliding copper on copper.[24]

In addition to being affected by the metal couple, friction and metal transfer are also grossly affected by the surrounding atmosphere. The gases of the atmosphere adsorb on the metal surfaces. This reduces their ability to weld or adhere (i.e. the adsorbed gas contaminates the surfaces). When these adsorbed gases are not present, coefficients of friction run upwards of 3 or 4 and complete welding or seizure of surfaces may result.[10] However, most friction and wear studies reported in the literature have been obtained under normal air atmospheres.

Although it has long been tacitly assumed that the adhesion mechanism is responsible for wear, it is only recently that direct evidence has been developed for loose wear debris generation from transferred metal.

Feng[23] had suggested that both friction and loose wear particles result from shearing of asperities that are interlocked rather than welded. The interlocking is considered a result of plastic roughening under the very high local pressures. However, available evidence[29,30,38] shows no appreciable generation of loose wear particles during the initial stages of the wear process. On the other hand, plastic roughening of the asperities may contribute to the exposure of nascent metal surfaces and subsequent adhesion.

It appears that, in many cases, the initial stage in the wear process is the transfer of metal fragments. These fragments are undoubtedly greatly modified in their physical and perhaps chemical properties as a result of the plastic working accompanying the transfer process. The fragments apparently tend to accumulate and become smeared together with more fragments. These localized "films" of smeared material may remain metallic in nature or may react with oxygen from the air to form oxides (Path II-III in Figure 7). In either case, they are repeatedly stressed severely with the result that the bond between the "film" and substrate metal surface may be broken and loose wear particles produced.[29,30] Besides this fatigue process, it appears likely that plowing off of the transferred film may be important, particularly for the more friable oxide films.[29]

Direct Corrosive Wear (Path III-I)

The wear process may also occur through direct corrosion of the bearing surface. It appears that the metal exposed by rubbing of surfaces may be particularly reactive.[43,45] Corrosion films may form through reaction with atmospheric oxygen or nitrogen to give oxides or nitrides; or with a reactive component of the lubricant to produce sulfides, chlorides, etc.

In some cases, the corrosion products may dissolve directly in the liquid lubricant. Most often, however, they remain on the surface as more or less coherent films, which may range from a few Angstrom units to many hundreds of Angstrom units in thickness (1 Angstrom Unit = 3.94×10^{-9} in.).

These films generally are less ductile than the substrate metal and are therefore subject to fracture. The friable nature of these films makes them subject to easy removal by plowing or fatigue (spalling). In addition, some of these films (e.g. ferrous chloride) are vulnerable to removal by reason of their low melting points.

The common feature of all these corrosion films is that they reduce the amount of metal-metal contact and, hence, the metal transfer wear. Table I illustrates that this may be accomplished by oxide films formed by air even when the surfaces are covered with a pure hydrocarbon lubricant. Corrosion films can also be generated by the lubricant. In fact, most mineral oils naturally contain com-

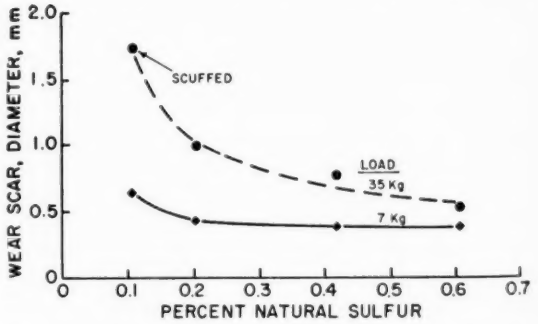

Figure 9 — Effect of Sulfur Content on Wear — SAE 30 Paraffinic Distillate Oils.

TABLE II

Corrosion Films Formed on Sliding Iron Surfaces

Lubricant Type	Properties of Film (Air Atmosphere) Nature	Coef. Fric. (Dry)	M.P., °C
Dry or Hydrocarbon	Fe	1.0	1535
	FeO	0.3	1420
	Fe_3O_4	0.5	1538
	Fe_2O_3	0.6	1565
Chlorine	$FeCl_2$	0.1	670
Sulfur	FeS	0.5	1193

pounds capable of generating sulfide films.[9] The wear reducing and anti-scuff influence of such materials is shown in Figure 9. In practice, materials containing sulfur, phosphorus, chlorine, etc. are added to enhance these properties of the lubricant.

These so-called E. P. (Extreme Pressure) agents* generally are more effective than the oxide films they replace, presumably because they form more durable or more easily sheared corrosion films. Thus, the critical physical properties of these films are their adherence to the substrate,[47] melting point, and shear resistance. Some properties of typical film on iron are shown in Table II.[7,28]

In the case of certain phosphorous compounds, such as tricresyl phosphate, it has been suggested that the corrosion product (Fe_3P) forms a low melting eutectic with iron; this is easily removed from high spots and thus may promote running in of surfaces by "chemical polishing".[5]

The rate of corrosion will influence the thickness of the corrosion film. The thicker the corrosion film the less likelihood of metal-metal contact with metal transfer, and ultimately wear particles (i.e. metal-transfer wear). However, the thicker the corrosion film the more rapidly the corrosion product tends to be plowed or spalled off (i.e. corrosive wear). It follows that increasing the chemical activity of a system should first reduce and then increase the total wear. The upper portion of Figure 10 illustrates this point.

The lower portion of Figure 10 illustrates that more corrosive (active E. P.) oils are generally capable of preventing catastrophic wear under more severe operating conditions (higher SAE machine loads in this case). Thus, it is apparent that use of corrosive agents must represent a compromise between minimum wear for any given set of conditions and acceptable wear levels over a wide range of operating conditions.

*These are called Extreme Pressure agents because of their ability to reduce wear under conditions of extreme pressures and temperatures.

Contributing Influence of Polar-Type Lubricants

As stated above, the use of E. P. films involves accepting a calculated loss through corrosive wear in order to reduce metal-metal contact. For most operating systems it is possible to maintain both sliding resistance and wear at much lower values than can be realized with simple corrosion films; this may be accomplished by covering or replacing the latter with polar-type lubricant films.

Polar-type films are formed by molecules consisting of long (e.g., hydrocarbon) chains with a polar functional group (e.g., hydroxyl, carboxyl, etc.) at one end. All conventional lubricants contain such molecules. In mineral oils they are present in small amounts (one percent or less) as carboxylate-type materials which occur naturally or as a result of processing. In animal and vegetable oils, and some synthetic lubricants, they are major components.

Such molecules are termed surfactive, since when present, for example, in hydrocarbon solution, they tend to "plate out" on any immersed high energy (e.g. metal, oxide, etc.) surface. The resulting film may be compared to the pile of a carpet, the polar groups being attached to the surface, and the hydrocarbon chains aligned approximately normal to it.[6]

The bond to the surface may range from the form of a relatively weak physical adsorption (e.g. dipole or Van Der Waal's forces) to a strong chemical bond. The former is typified by the case of octadecyl alcohol on copper. The latter is typified by the case of stearic acid reacting on iron or iron oxide to form a soap (iron stearate).

The conditions for chemical reaction between the metal surface and the adsorbed molecules to form soaps are quite critical and depend on the condi-

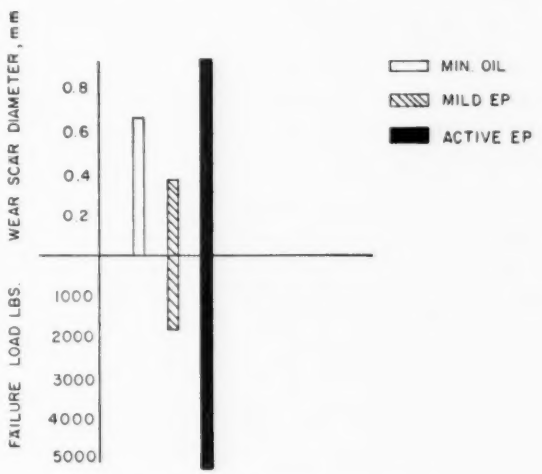

Figure 10 — E.P. Activity and Wear.

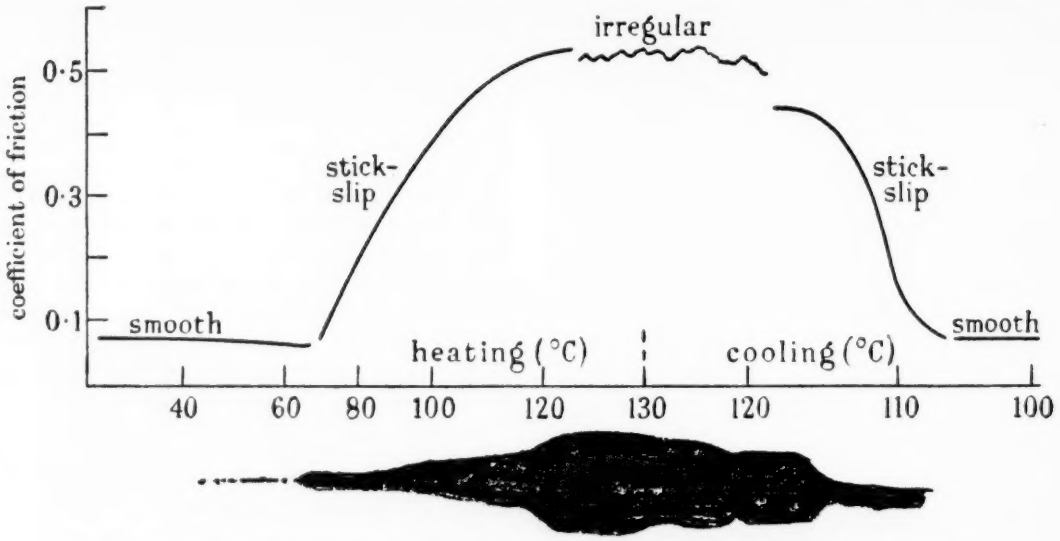

Figure 11 — Effect of Temperature in Sliding Cadmium on Cadmium in the Presence of Palmitic Acid.

tion of the surface as well as its environment. This is particularly so when the film has been deposited from a dilute hydrocarbon solution; here it appears that even with carboxylic acids adsorbed on reactive metals, the presence of oxygen and water at the surface is necessary for the phenomenon to occur at a discernible rate.[26,27,44,46] Derivative of carboxylic acids, such as esters, may also form soaps but with less facility than the acids themselves.[12]

The properties of these polar films have been only poorly defined. However, two generalities may be made, based mainly on electron diffraction evidence.[14,34]

(1) The films undergo "two-dimensional melting" at a temperature close to the bulk melting point of the film material. This so-called "disorientation temperature" distinguishes physically adsorbed films from soaps, because of the considerably higher melting points of the latter.

(2) While physically adsorbed films become detached from the surface at their "melting points," the attachment of soap-type films persists to some degree even though "melted."

These observed characteristics may be directly associated with the lubricating properties of the films. When metal surfaces containing them are slid over each other at slow speeds, low coefficients of friction are observed; these are only a fraction of the values obtained with typical corrosion films. If the temperature of the system is increased, a sudden increase in friction and metal transfer is noted at approximately the "melting point" of the film material.[12,34] When soap formation has occurred at the surface, this transition occurs near the "melting point" of the soap rather than of the acid employed. Also, in such cases the increase in friction and transfer is followed by a second increase at some further elevated temperature.

Some of the points mentioned above are shown by Figure 11.[40] This gives the results of sliding a radioactive cadmium rider on a cadmium plate covered with a smear of palmitic acid, while the temperature was first raised and then lowered again. The friction was continuously recorded, and a record of the metal transfer was obtained from an autoradiograph of the plate. Two transitions are noted in both the ascending and descending temperature regions, the lower one attributed to "melting" of the film and the higher one to desorption. The "melting point" in the ascending temperature region corresponds well to that of palmitic acid; however, that in the descending region is considerably higher.

TABLE III

Friction and Transfer for Cadmium Surfaces at Room Temperature

Lubricant	Coefficient of Friction	Metal Pick-up X 10^9 gm/cm of Track
None	0.8	50,000
Cetane ($C_{15}H_{31}CH_3$)	0.6	500
Cetyl alcohol ($C_{15}H_{31}CH_2OH$)	0.4	100
Palmitic acid ($C_{15}H_{31}COOH$)	0.07	1

indicating that soap formation was accelerated by the high temperatures.

It appears, then, that polar-type films, more particularly those chemically bound as soaps, are capable of dramatically reducing metal-metal interaction during sliding, and that this protection is in some way associated with the "solid" state of the film and its adherence to the metal.

The reason for this reduction has not been clearly established at present. It may be a simple prevention of welds by surface contamination. Another possibility is that these films are scraped from the surfaces during sliding and are wedged between approaching asperities. A third possibility is illustrated by Figure 12.[12] Here the film is shown separating the metal surfaces over part of the real area of contact between the surfaces, thereby reducing the area of metal-metal contact needed to support the load. Sliding experiments using radioactive techniques support this last picture since they indicate that soap-type films reduce the size (and not the number) of metal-metal contacts.[40]

When sliding occurs, friction may be looked upon as the sum of the force required to shear the metal-metal junctions and the force required to shear the adsorbed film. Starting with this latter concept and making a number of assumptions permits derivation of a relationship between metal transfer and coefficient of friction.[39] This derived relationship is shown graphically in Figure 13 using typical values for the coefficient of friction of the lubricant film, f_l and of the metal junctions, f_m. Experimentally, curves of this general type have been obtained for wear as well as for metal transfer.[39] The curve points up the insensitivity of coefficient of friction to large changes in metal transfer in systems where the friction is low. This is in agreement with experimental indications that the friction with effective boundary lubricants is

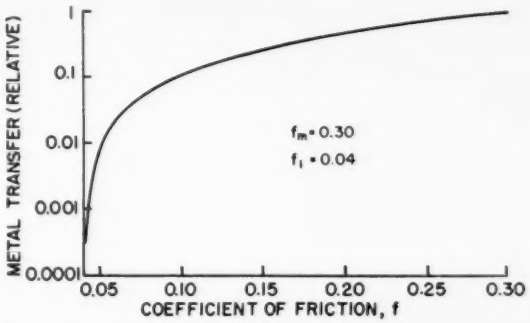

Figure 13 — Example of Theoretical Metal Transfer — Wear Relationship.

primarily made up of the force required to shear the lubricant film.[3,40] Further evidence for this insensitivity is given in Table III[40] where an elevenfold increase in the coefficient of friction is associated with a 50,000-fold increase in metal transfer. This table also illustrates the decreasing friction and metal transfer with increasing strength of the bond to the surface.

It is of interest to consider the degree of metal involvement with these various polar films. Removal of the cetane, alcohol or unreacted acid films from the surface by sliding represents no loss of substrate metal as part of the film. However, when the acid reacts with the metal to form a soap, the resulting film must be considered a corrosion product. Removal of this material involves a metal loss which is small compared to the case of corrosion films previously discussed.

INTERPRETATION OF LUBRICANT PERFORMANCE

It would appear from the previous remarks that optimum wear prevention might be obtained by employing lubricant combinations capable of forming more than one type of film. This idea is presented schematically in Figure 14[12] which shows how the

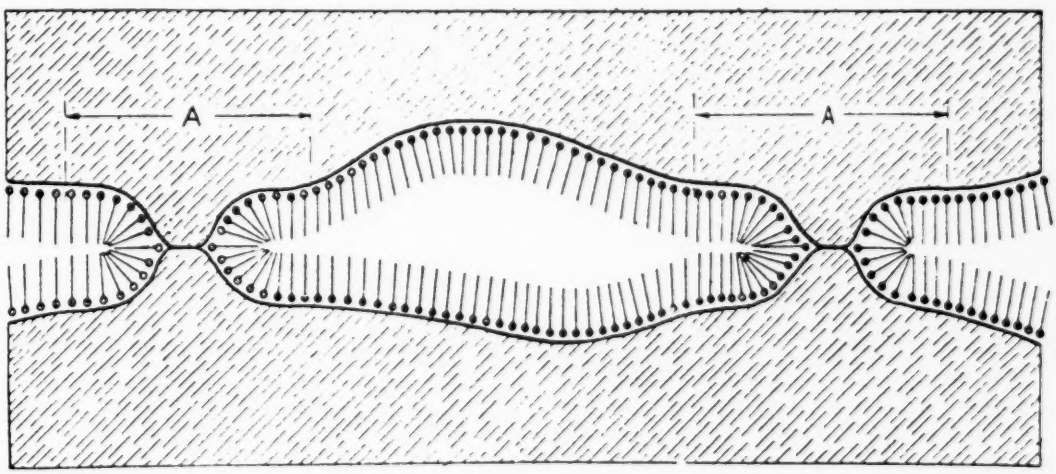

Figure 12 — Contacting Surfaces in the Presence of a Polar-Type Lubricant.

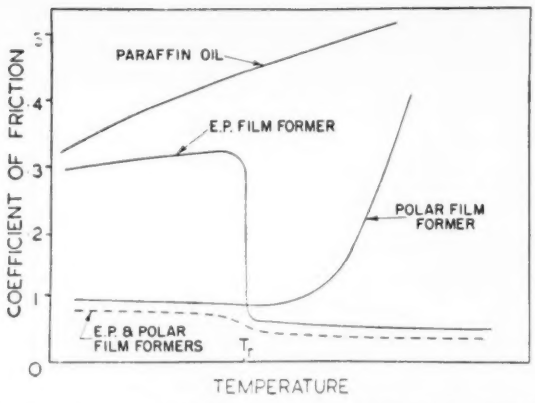

Figure 14 — Schematic Frictional Behavior of Lubricants with Increasing Temperature.

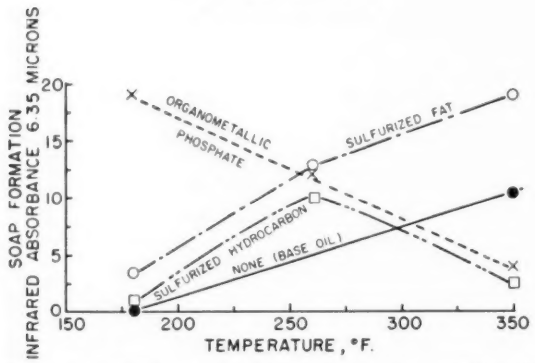

Figure 15 — Effect of E.P. Agents on Soap Formation in Oil/Iron Systems.

friction (and wear) might be expected to vary with temperature (or load) for soap and E.P. film forming agents alone and in an idealized combination. If at some surface temperature, T_r, where the soap film loses its effectiveness, an E.P. agent becomes active, protection would be obtained over a wide range of conditions. Practically, such a superposition of effective ranges of activity may be either helped or hindered by interactions between components. One example of such interactions is provided by Figure 15, which shows the results of studies in which combinations of conventional mineral oil and various E.P. type compounds were contacted with iron powder at various temperatures. The amount of soap formed on the powder by the carboxylate materials in the mineral oil was measured by desorption and infrared analysis. It is seen that the effect of these E.P. compounds on soap formation may be very marked, and varies with the compound and with the temperature.

In addition to the E.P. compound affecting soap formation, the soap film former may interfere with functioning of the E.P. film. This is shown by Figure 16 for what is essentially "run-in" wear. The "E.P. oil" containing only an organometallic phosphate (abbreviated org. phosphate in Figures)

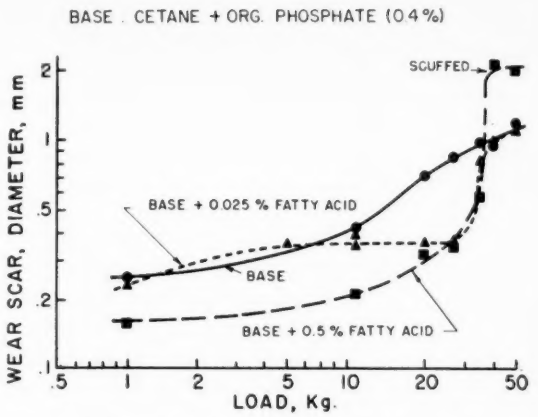

Figure 16 — Effect of Fatty Acid on E.P. Action.

in cetane prevents scuffing throughout. Adding a small amount of a fatty acid (i.e. the soap former) reduced the wear at intermediate loads, while still preventing scuffing at high loads. Addition of a larger amount of acid, however, induced scuffing at high loads even though it further reduced the wear at lower loads. Such results might be explained in terms of competition for the surface between the two types of film formers.

In some cases, as shown in Figure 17, the E.P. agent may actually improve the antiwear action of the soap film at moderate loads. In the "steady state" region following run-in, the added E.P. agent markedly decreases the wear rate below that obtained with fatty acid alone. This action may be attributed to inhibiting oxidative degradation of the soap film or possibly to superposition of the two films.

In general, it appears that practical lubrication problems resolve into establishing optimum balance between corrosive wear prevention on one hand, and protection against metal-to-metal contact on the other. This balance must be maintained over the range of environmental and operating conditions in which a mechanism operates. It is clear that the requirements for preventing corrosive piston ring

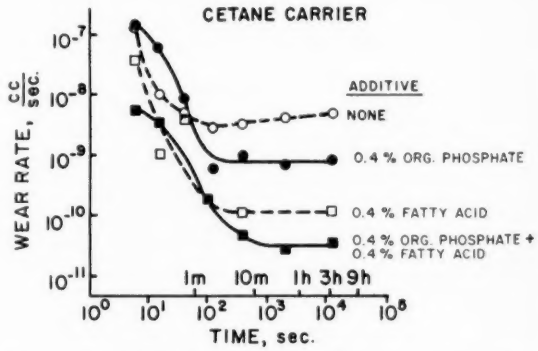

Figure 17 — Effect of Fatty Acid and Organometallic Phosphate on Wear Rate.

TABLE IV

Load-Carrying Performance of Additives in Diester Blends

Additive	Gear Test Tooth Load, lb/in
Phosphate (2%)	1740
Acid (0.05%)	2020
Phosphate (2%) + Acid (0.05%)	2670
Phosphate (2%) + Acid (0.05%) + Detergent (4%)	1690

wear at low temperatures will be different from the requirements for preventing the failure of heavily-loaded gears. Figure 18, for example, shows the large wear-reducing effect of typical detergent additives on corrosive ring wear in automotive engine operation. These materials function through their corrosion barrier, sequestering and acid-neutralizing effects, rather than through any appreciable load support action. The effect of the organometallic phosphate E.P. additive is small by comparison. On the other hand, Table IV presents a case where a lubricant balanced to give maximum load support in the Ryder gear scuff test is degraded by the addition of a typical detergent. It appears that the above mentioned properties of a detergent may interfere with the formation of load-support films.

Similarly the requirements for optimum reduction of low temperature piston ring wear in automotive engines differ from those for valve train wear reduction, which primarily demands load-support films. This is illustrated in Table V where the above mentioned detergent effects are again evident. These results show that simple lubricant combinations which reduce one type of wear often tend to increase the other type.

Since the same lubricant must satisfactorily perform in both the ring belt and valve train areas of an engine, it would seem that an automotive motor oil must represent a balance between these (and other) functions. It is possible to improve on a simple balance by adding additional surfactant materials. If properly chosen, these added components may interact to enhance one or more functions while not degrading any other functions of the lubricant.

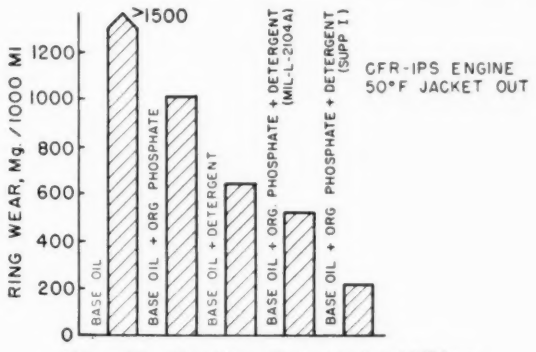

Figure 18 — Ring Wear Reduction by Additives.

Lubricant formulations must consider the nature of the bearing metals as well as the operating conditions. Although certain classes of organometallic phosphates are proven antiwear agents in most common practice, many of these same compounds do not satisfactorily lubricate silver on steel bearings found in some mechanisms. Table VI shows the relative friction force for sliding steel on silver for a number of combinations of E.P. type compounds and detergents in a base oil. The organometallic phosphate consistently showed the highest friction, sulfurized fat the lowest, and the sulfurized hydrocarbon showed intermediate behavior strongly influenced by the nature of the detergent.

The above problems are typical of the many encountered in lubricant formulation where obscure interaction effects necessitate the use of empirical methods to achieve practical solutions. All such interaction effects must be understood before the lubrication problems of friction and wear can be more efficiently and intelligently attacked. The clarification of these interactions, in their turn, must await a fuller understanding and appreciation of the basic processes outlined in this review.

TABLE V

Effect of Detergents on Wear

Detergent	Wear Level[1] Low Temp. Ring Wear	Hydraulic Valve Lifter Wear
None	ca. 2.2	ca. 0.5
A	1.7	0.7
B	1.5	0.2
C	1.4	3.6
D	1.1	2.0

[1]Arbitrary units

TABLE VI

Effect of Detergent-E.P. Agent Combinations on Silver-Steel Lubrication

Detergent	Friction Torque Org. Metallic Phosphate	Sulfurized Hydrocarbon	Sulfurized Fat
A	>1000	518	470
B	>1000	595	480
C	>1000	>1000	375

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